

**Ar-Ar analysis of Chelyabinsk: Evidence for a recent impact.** S. P. Beard<sup>1,2</sup>, D. A. Kring<sup>2,3</sup>, C. E. Isachsen<sup>4</sup>, T. J. Lapen<sup>2,5</sup>, M.E. Zolensky<sup>2,6</sup>, T. D. Swindle<sup>1,2,4</sup>, <sup>1</sup>Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721 ([spbeard@lpl.arizona.edu](mailto:spbeard@lpl.arizona.edu)), <sup>2</sup>Center for Lunar Science and Exploration, National Lunar Science Institute, <sup>3</sup>Lunar and Planetary Institute, Houston TX, <sup>4</sup>Geoscience Department, University of Arizona, <sup>5</sup>University of Houston, Houston TX, <sup>6</sup>NASA-Johnson Space Center, Houston TX

## Introduction:

The Chelyabinsk meteorite is an LL5 ordinary chondrite that fell as a spectacular fireball on February 15<sup>th</sup>, 2013, over the Ural region in Russia. The meteoroid exploded at an altitude of 25-30 km, producing shockwaves that broke windowpanes in Chelyabinsk and surrounding areas, injuring some 1500 people. Analyses of the samples show that the meteorite underwent moderate shock metamorphism (stage S4; 25-35 GPa) [1]. Most of the samples have a fusion crust ranging from ~0.1-1mm thick, and roughly a third of the samples were composed of a dark fine-grained impact melt with chondrule fragments which were targeted for chronometry.

A Pb-Pb age obtained by [2] of a shock-darkened and potentially melted sample of Chelyabinsk is reported as  $4538.3 \pm 2.1$  Ma, while a U-Pb study [3] gave an upper concordia intercept of  $4454 \pm 67$  Ma and a lower intercept of  $585 \pm 390$ . Galimov et al. 2013 [1] suggest the Sm-Nd system records a recent impact event [ $\sim 290$  Ma] that may represent separation from the parent body, while the Rb-Sr isotopic system is disturbed and does not give any definitive isochron. In order to better understand its history, we have performed  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  analysis on multiple splits of two Chelyabinsk samples; clast-rich MB020f,2 and melt-rich MB020f,5. The term “clast-rich” lithology is meant to indicate a mechanical mixture of highly shock-darkened and less shocked components, both with some shock melt veining.

## Approach:

Samples of Chelyabinsk were irradiated at the Cadmium-Lined In-Core Irradiation Tube (CLICIT) facility at Oregon State University along with PP-20 Hb3gr Hornblende GSC as the primary irradiation monitor ( $1080.4 \pm 1.1$  Ma, [4]) to determine the J-factor. Samples were irradiated for 4 hours in the linear-with-height portion of the reactor to provide a more evenly distributed neutron flux. Argon was extracted from each sample using a computer controlled step-heating procedure with a double-vacuum resistance-heated furnace. Typical temperature steps were from 300-1500 °C in 50-100 °C intervals, totaling 15-30 heating steps per split, adjusted to obtain the desired accuracy as needed. Each step was heated for 12 minutes and, after gettering, analyzed in a VG5400 mass spectrometer. The decay constants used are those reported in [4]. Uncertainties and corrections were applied to account for blanks, machine

discrimination and interfering isotopes produced in the reactor from Ca and K.

## Results:

The four splits of the clast-rich MB020f,2 (SB1, SB2, SB3, and CH1) have low apparent ages for the first ~85% of the total  $^{39}\text{Ar}$  released, before increasing, typically to ~2000 Ma to ~3000 Ma, in the highest-temperature extractions. Three of the splits give a series of concordant ages with an average age of  $28.6 \pm 3.3$  Ma, which represents our best estimate of the most recent thermal event for Chelyabinsk (Figure 1).

The three melt-rich MB020f,5 splits (SB4, SB5, and CH2) do not agree as well as the clast-rich sample, but the overall classic diffusion pattern, with higher ages at higher temperatures, is seen in each of these splits. None of the splits have an apparent age as low as the partial plateaus in the clast-rich splits. The high temperature steps have apparent ages as high as ~3500 Ma, which represents a lower limit to the age of a previous event (Figure 1). However, that previous event could be the older event recorded in the Pb-Pb system. An argument could be made for a partial plateau in the apparent age spectra of CH2, with an age of  $2809.3 \pm 12.8$  (temperature steps 975-1400°C), containing 57% of the released  $^{39}\text{Ar}$ . However, we do not put much confidence in this age, as there is no other evidence to support an event at this time.

## Discussion:

This work shows evidence of a recent heating event in Chelyabinsk MB020f,2 at  $28.6 \pm 3.3$  Ma, which is significantly younger than other known LL chondrites. In fact, it is more recent than any other impact event recorded in an ordinary chondrite by  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating. Most LL chondrites have impact ages of 4200-4350 Ma [5] with very few examples of resetting in the last 1500 Ma. The youngest  $^{40}\text{Ar}$ / $^{39}\text{Ar}$  ages are for the LL impact melts Yamato-790964 ( $1260 \pm 24$  Ma) [6], NWA 1701 ( $970 \pm 80$  Ma) [5], and LAR 06298/9 (LLIM) with an  $^{40}\text{Ar}$ / $^{39}\text{Ar}$  age of  $<400$  Ma [7,8] and the LL6 Morokweng fossil meteorite ( $625 \pm 163$ ) [9]. This new result provides additional data that is important for understanding the evolution and recent history of the LL chondrites, which may include a shared past with the Hayabusa target asteroid 25143 Itokawa, identified as an LL chondrite [10]. If a  $^{40}\text{Ar}$ / $^{39}\text{Ar}$  age can be obtained on Hayabusa samples, it can help determine

whether Chelyabinsk and Itokawa have a common history.

Our results are consistent with the Sm-Nd analyses of Chelyabinsk. The Sm-Nd system [1] has clearly been disturbed recently, and it appears that a 28 Ma isochron would be nearly as good a fit as the 290 Ma isochron they present. Studies using both Pb-Pb [2] and U-Pb [3] indicate ages of >4400 Ma (although they are not in complete agreement), and the U-Pb data gives a poorly-defined younger age ( $585 \pm 390$  Ma) that is basically consistent with the Ar-Ar result. It is somewhat puzzling that the Sm-Nd system appears to have experienced more resetting in the recent event than the U,Th-Pb system, but there is evidence of some relatively recent event in all isotopic systems that have been studied. Only in the Ar-Ar data is the time of the event defined well. The Ar-Ar results are particularly complementary with the U-Pb data. The Ar work shows evidence of a poorly-defined older event, whereas the U-Pb work has a well-defined older age. The Ar work has a well-defined younger age, whereas the U-Pb work shows some traces of a younger event.

The clast-rich sample yields younger apparent ages than the melt-rich sample, indicating that it was more thoroughly degassed in the most recent event. Although this seems counterintuitive, this is not unusual behavior [e.g., 11,12]. An obvious question to ask is whether the clast-rich sample's young apparent age is a result of heating during Chelyabinsk's entry in the atmosphere and subsequent explosion. However, to drop the apparent age to 28 Ma from 4000 Ma would require that 99.8% of the argon to be degassed, and there is no evidence seen in the petrography for such extreme heating of the interiors of samples during this event. Therefore, we believe the 28.6 Ma age in fact does represent an impact event.

### Conclusion:

Chelyabinsk MB020f,2 shows strong evidence of a recent thermal event at  $28.6 \pm 3.3$  Ma, which is significantly younger than other known LL chondrites. Chelyabinsk MB020f,5 has a hint of an older thermal event at > 3500 Ma. This is consistent with U-Pb work by Lapen et al. [3], whose work shows evidence of a well-defined older event, and evidence of some poorly defined recent event. The older event seems to be the stronger one, as it reset the U-Pb system completely, while the younger event did not.

### References:

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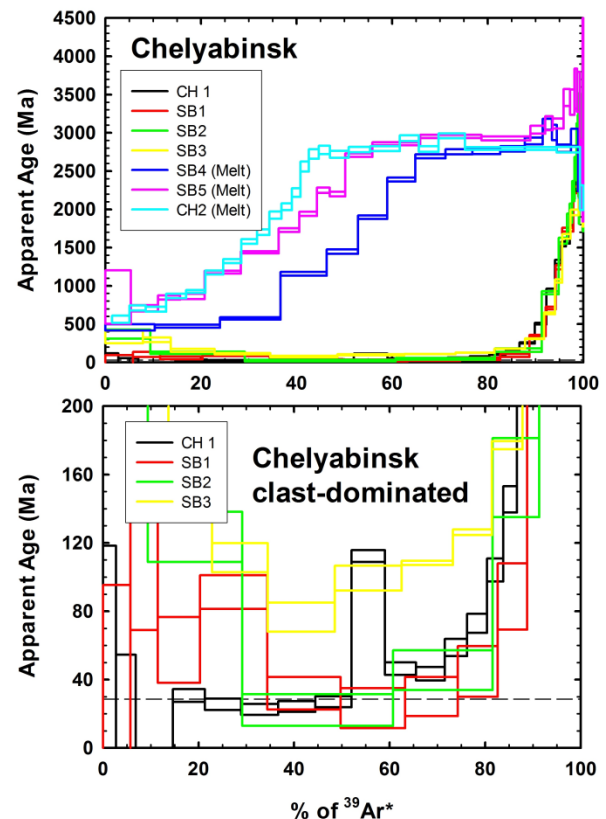


Fig. 1) Apparent age spectrum of Chelyabinsk MB020f,2 (Clast-rich) and MB020f,5 (Melt-rich). The melt-rich splits show a diffusion pattern and evidence of a prior thermal event > 3500 Ma. More interestingly, the clast-rich sample (bottom figure) shows that a recent thermal event occurred at  $28.6 \pm 3.3$  Ma.